The International Journal of Advanced Manufacturing Technology (2019) 104:1211–1219
https://doi.org/10.1007/s00170-019-04016-2

ORIGINAL ARTICLE

Research on surface modification of anodized aluminum alloy using piezoelectric machine hammer peening

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Received: 27 November 2018 / Accepted: 17 June 2019 / Published online: 3 July 2019

Abstract
Piezoelectric machine hammer peening (PEMHP) is a mechanical surface treatment method that hammers the workpiece surface by an oscillatory spherical tungsten carbide tool. The experiments have been conducted to investigate the surface modification of 6016 anodized aluminum alloy using PEMHP, including surface roughness, surface topography, and hardness. The experimental and simulation results indicated that PEMHP has better surface smoothing effect than milling and improves the surface integrity. The hardness of anodized aluminum alloy increases about 14–33% with different peening parameters. The influences of peening parameters on surface roughness, surface topography, and hardness are discussed. It is found out that peening parameters have strongly influenced surface integrity, especially line pitch. Therefore, PEMHP can be a subsequent machine process for aluminum alloy after anodic oxidation to improve surface integrity and hardness further.

Keywords Piezoelectric machine hammer peening · Surface roughness · Surface topography · Hardness · Peening parameters

1 Introduction

Aluminum alloy is an important lightweight material and used more and more in car or aviation industry, especially 6016 aluminum alloy. To improve the aluminum alloy surface hardness, anodic oxidation is an effective method. Hence, it is a key machine process. However, anodic oxidation causes the cellular structures of the surface and increases the surface roughness of aluminum alloy parts, which is bad for the high-precision parts. The conventional smoothing methods are based on removing material mechanism to reduce the surface roughness. These methods remove the compact oxidation film that is generated in the anodic oxidation process and change the mechanical property completely. It is obvious that the conventional smoothing methods are not suited for anodized aluminum alloy to improve surface integrity. In addition, the smoothing or finishing of aluminum alloy parts has relation to abrasive resistance, corrosion resistance, and strength. Therefore, it needs a new smoothing technology for this requirement.

In the development of a new technology for surface processing, the emphasis was placed on making the process as precise, reliable, and highly efficient as possible. Machine hammer peening (MHP) is a mechanical surface treatment that hammers the workpiece surface using a spherical tungsten carbide tool. Compared with other mechanical treatments, MHP not only obtains good integrity of workpiece surface without remove material but also has advantage in generation of compressive residual stresses and strain-hardened layer on the surface of workpiece. It is also different from shot peening (SP) that MHP can be controlled by a machine tool or robot, which can achieve the precision displacement requirement. The actuation of the spherical tungsten carbide tool is either electromagnetic, pneumatic, or piezoelectric [1–3]. It is a potential smoothing technology for the anodized aluminum alloy.

In the preliminary work of Wied's [4, 5] master's thesis, it is reported there that the MHP process smoothens and hardens the workpiece surface, and the surface smoothing effect of MHP by finite element simulations is researched, which established good agreement with the experimental results. Berglund et al. [6] evaluated whether the MHP method could

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become a plausible substitute for manual polishing in pressing die and nodular cast iron samples that were hammered. Bleicher et al. [7, 8] found that the main positive effects of MHP are the induction of compressive residual stresses, the hardness increase of the upper surface layer, and a reduction of surface roughness up to mirror-like surface, and the tribological characteristics of the tool and mold can be improved by MHP. Lechner et al. [9] sought to explore the effects of several process parameters and how these parameters have to be optimized for surface smoothening of a C45E steel sample. With robotic technology, Krall et al. [10] investigated the static and dynamic behavior of the 6-axis industrial robot during the hammer peening process to evaluate the applicability to generate deterministic patterns. In order to automate the machining of complex workpiece surfaces with MHP, KUKA (https://www.kuka.com/en-de/industries/solutions-database/2016/07/solution-robotics-sematek) turns to a robot with KUKA.CNC software. Chen et al. [11] indicated that MHP has a beneficial influence on the corrosion resistance, indicated by a significant increase of the critical pitting potential accompanied with lower corrosion current density and higher polarization resistance. Trauth et al. [12–14] focused the influence of surface textures manufactured by MHP on tribological interactions including the fluid film, velocity distribution, and spreading pressure of lubrication. In addition, MHP can be used to release stresses close to the surface and preserve the mechanical and dimensional properties of manufactured components, thereby improving the fatigue resistance [15, 16].

It is noticed that most of the research studies are done based on electromagnetic or pneumatic MHP in the literature instead of piezoelectric MHP. The main objective of the present study was to discover the effect of 6016 anodized aluminum alloy surface modification by piezoelectric machine hammer peening (PEMHP) and evaluate whether PEMHP could become an effective method to improve surface integrity or hardness of 6016 anodized aluminum alloy. The surface roughness, surface topography, and hardness were investigated. Furthermore, the selections of peening parameters for better surface integrity and hardness were discussed.

2 Experimental setup

The 6016 anodized aluminum alloys were hammered by a spherical tungsten carbide tool that is driven by a piezo actuator. The piezo actuator system includes a piezo actuator, waveform generator, and power amplifier. The piezo actuator and spherical tungsten carbide tool were installed in a hammer part, which was attached to a 3-axis CNC machine center, as shown in Fig. 1 (a) and (b). The peening tool path and the main peening parameters are illustrated in Fig. 1(c). The peening parameters include tungsten carbide tool diameter D, line pitch s, feed rate v_s, peening frequency f, and peening amplitude a_p. The line pitch and feed rate are determined by CNC machine tool programming, while the frequencies and peening depths are controlled by the piezo actuator with assisted waveform generator and power amplifier. The piezo actuator is manufactured by Harbin Core Tomorrow

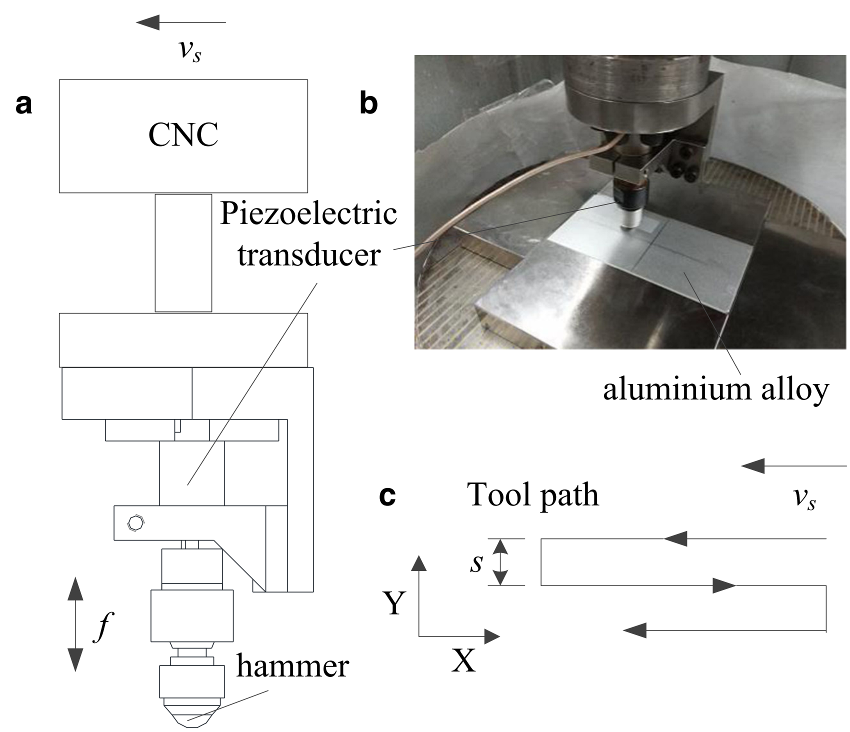

Fig. 1 (a) Principal design of PEMHP. (b) Experimental setup. (c) Tool path

Table 1 Peening parameters

Peening parameters	Values
Tungsten carbide hammer diameter D (mm)	10
Line pitch s (mm)	0.1, 0.2, 0.3, 0.4
Feed rate v_s ($mm \cdot s^{-1}$)	25
Peening frequency f (Hz)	100, 200, 300, 500
Peening amplitude a_p (μm)	19

Science&Technology Co., Ltd., and the model is PSt 150/7/20 VS12 (stroke 19 μm, rigidity 60 N/μm, thrust 1200 N, electrostatic capacity 1.8 μF). The ranges of peening parameters values used in experiments are listed in Table 1. The surface roughness, surface topography, and hardness after PEMHP were investigated. The values of surface roughness were measured by Taylor Hobson PGI Dimension 3 Profiler in parallel and vertical hammer direction, and the larger one in two directions was adopted. The results were based on mean values of four measurements. The roughness measurements were analyzed using the software Ultra 5.24.1.61 and presented as arithmetic mean deviation Ra. The surface topographies were observed by a Kenyence VHX-2000C microscope. Moreover, the dimensions of microstructures like scallops and scratches, especially peened track, can also be measured. Surface hardness measurements were made using a HV-10B Low Load Vickers hardness tester. The results were obtained by calculating the dimensions of indentation.

3 Analysis of experimental and simulation results

3.1 Surface roughness

Figure 2 shows machining mechanism of PEMHP and indicates that the residual peak and valley (PV) error is determined by the line pitch and distance between two hits, when tungsten carbide hammer diameter has a certain value. It is easily explained that the residual PV errors between two hits in two directions are the main cause of surface roughness generation. The surface roughness can be expressed as PV error similarly for simulation. The value of PV error can be expressed as follows,

$$\mathrm{PV} = D/2 - \sqrt{D^2 - s^2}/2 \tag{1}$$

where s is the line pitch or distance between two hits s'. The distance between two hits can be described as follows,

$$s' = v_s/f \tag{2}$$

Equation 1 is derived by differentiating with respect to D and s, and subtraction of two derivatives λ_{D-s} are calculated as follows,

$$\lambda_{D-s} = 1/2 - 1/\sqrt{(D+s)/(D-s)} \tag{3}$$

Because D is much larger than s, the value of λ_{D-s} is less than zero, which means PV is most sensitive to line pitch, rather than hammer diameter. In addition, piezoelectric transducer can reach high peening frequency and machining efficiency and the influence of feed rate is ignored. Therefore, the line pitch and peening frequency are deemed as two key peening parameters.

The surface roughness values are measured by Taylor Hobson PGI Dimension 3 Profiler, and the measurement parameters are listed in Table 2. Ruby stylus is not suited for aluminum alloy measurement due to material compatibility; therefore, diamond stylus is adopted.

The surface roughness values of 6016 anodized aluminum alloy by different treatment methods are presented in Fig. 3. Each surface roughness value was adopted by averaging each experimental result. It is found that the surface roughness value after anodic oxidation is larger than milling one. Compared with anodic oxidation, the surface roughness values after PEMHP decreased about 71% ($s = 0.2$ mm, $f = 500$ Hz, $v_s =$

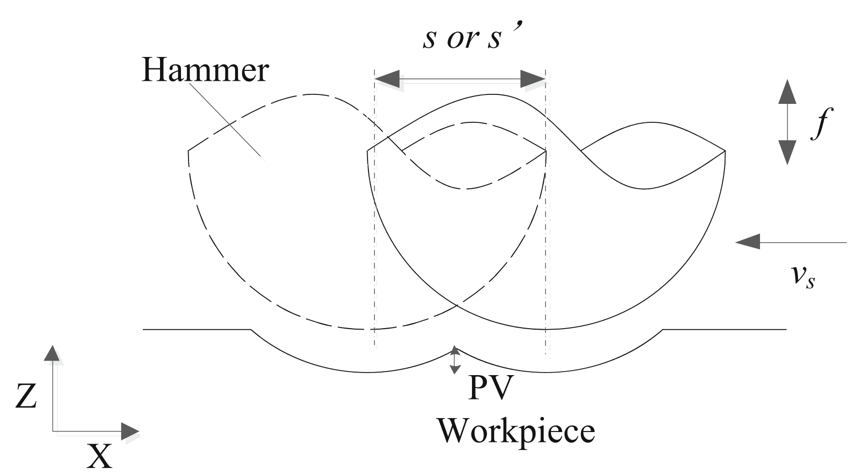

Fig. 2 Diagram of PEMHP and surface roughness generation

Table 2 Measurement parameters (Taylor Hobson)

Parameters	Values
Diamond stylus radius (μm)	2
Scan speed (mm s^{-1})	0.25
Sampling interval (μm)	2
Resolution (nm)	0.2

25 mm/s, $D = 10$ mm, $a_p = 19$ μm). Therefore, the PEMHP can be an anodic oxidation subsequent machine process for improving 6016 aluminum alloy surface integrity, which is also an alternative solution instead of grinding.

It is found that the large line pitches lead to large surface roughness values and have great influence on surface roughness from Fig. 4. Especially when line pitches larger than 0.2 mm, the surface roughness values go up faster. Figure 5 shows the relation of surface roughness values and peening frequency. The surface roughness values are decreased with increasing of peening frequency. Compared with peening frequency, surface roughness is more sensitive to line pitch. Simulation results are calculated based on Eq. (1) and fit experimental results well but a little different due to simplification of simulation and experimental environment. To reduce the surface roughness values, the line pitch is the most key parameter that should be controlled.

It is well known that SP increases the surface roughness sharply, and it is not a suitable method for smoothing surface. The ultrasonic nanocrystalline surface modification (UNSM) is another surface processing technology that is used to improve the material properties. UNSM has been utilized to decrease the aluminum alloy's surface roughness, and the value of roughness can reach to 0.028 μm, which is much better than PEMHP [17].

3.2 Surface topography

According to machining mechanism of PEMHP, the line pitch and the distance between two hits have great influence on surface topography. Various combinations of line pitch and distance between two hits cause two types of surface topography as shown in Fig. 6. When $s > s'$, the simulation of surface topography are shown in Fig. 6 (a) and (c), otherwise, shown in Fig. 6 (b) and (d). The surface modification in peening direction is caused by the peening frequency and feed rate, and the line pitch is a dominant parameter in vertical peening direction.

The 6016 anodized aluminum alloy by PEMHP with different line pitches is presented in Fig. 7. The distance between two hits is 0.05 mm and smaller than the line pitch, results of which conform to surface topography shown in Fig. 6 (a) and (c). It is also observed that the peening track is obvious when the line pitch is 0.4 or 0.3 mm.

Figure 8 shows the surface topography of the original 6016 anodized aluminum alloy surface and peened surface at × 50 magnification. It is obvious that lots of scallops distribute throughout the anodic oxidation surface in Fig. 8(a). Figure 8 (b–e) shows the surface topography of PEMHP samples with different frequencies. When the peening frequency reaches to 300 Hz or more, the scallops almost disappear. With the increasing of peening frequency, the hammer peening surface is much smoother.

Figure 9 shows the surface topography of PEMHP samples with different line pitches at × 50 and × 20 magnifications. It is pointed that the large line pitch makes the surface tracks clear after peened, which is more obvious by comparison of $s = 0.1$

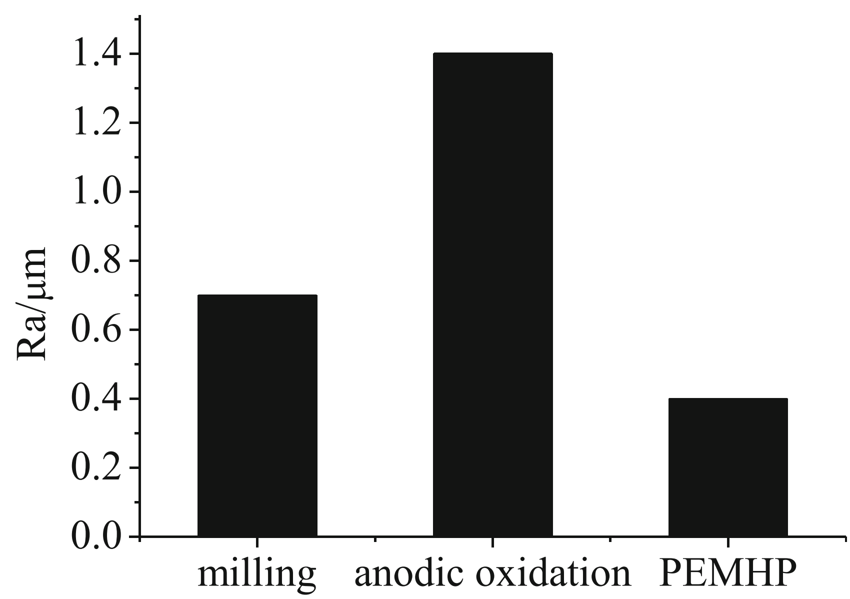

Fig. 3 Comparison of surface roughness by three treatment methods

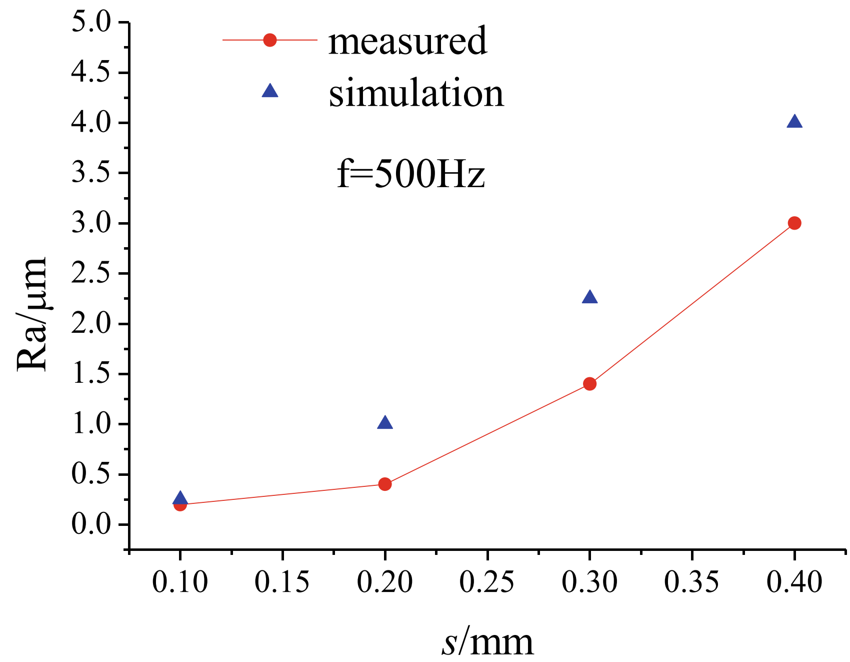

Fig. 4 Relation of surface roughness and line pitch

and $s = 0.4$ at × 20 magnification from Fig. 9(d) and (e). When the line pitch is equal to 0.2 mm or less (Fig. 9b, c), the surface tracks are almost gone at this magnification. The distance between two peened tracks can be also measured using a Kenyence VHX-2000C microscope. The measured results are approximately equal to the line pitch as shown in Fig. 9(a). As a result, the line pitch has strong influence on surface topography and a small line pitch is suggested. Compared with simulation of surface topography in Fig. 6, the experimental results fit well.

3.3 Surface hardness

Machine hammer peening is similar to shot peening in improving workpiece hardness. Theoretically, PEMHP should have the same effect of improving surface hardness. The hardness was tested by a Vickers hardness device, with 5 N force and 15 s dwell time. After four times of measuring and calculating each, the average hardness distributions along the depth under different peening parameters are shown in Fig. 10. It is found that the original 6016 anodized aluminum alloy surface

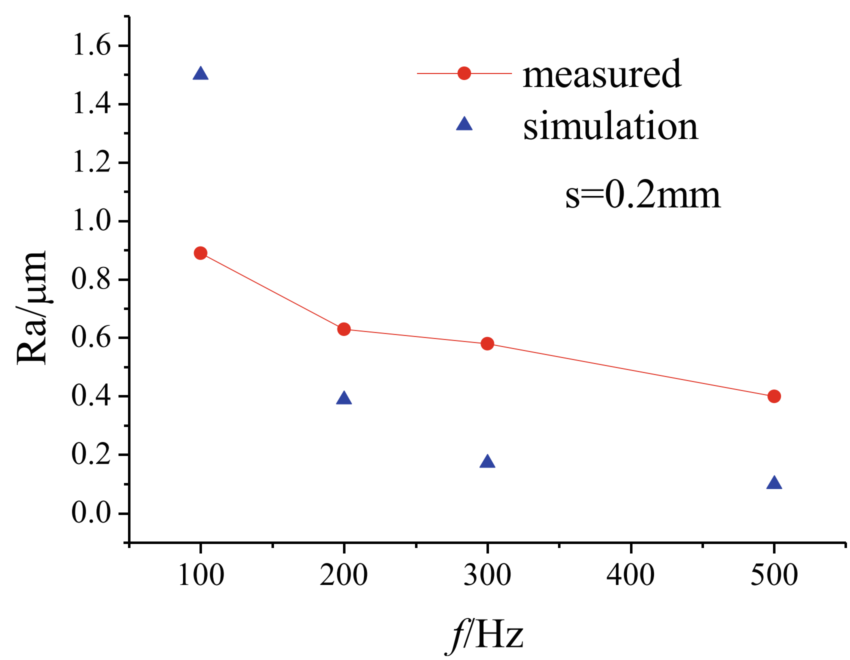

Fig. 5 Relation of surface roughness and peening frequency

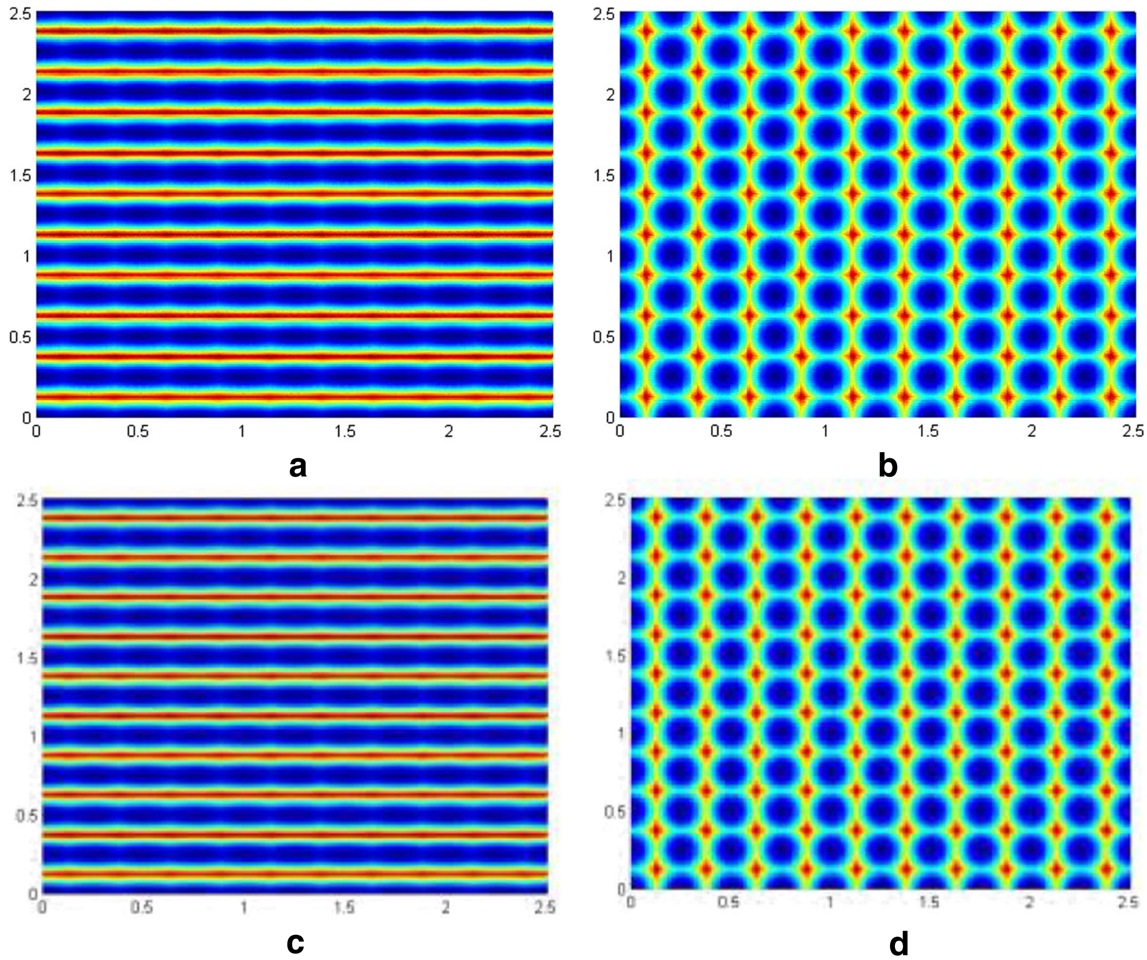

Fig. 6 Surface topography of PEMHP by simulation. (a) $f = 100$ Hz, $s = 0.2$ mm, $v_s = 5$ mm/s. (b) $f = 100$ Hz, $s = 0.2$ mm, $v_s = 25$ mm/s. (c) $f = 500$ Hz, $s = 0.2$ mm, $V_s = 25$ mm/s. (d) $f = 100$Hz, $s = 0.4$ mm, $v_s = 25$ mm/s

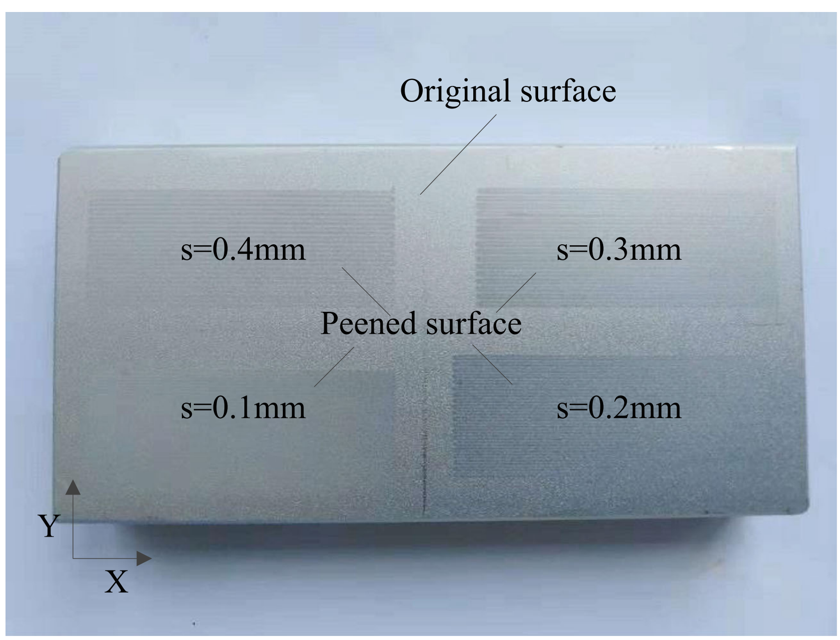

Fig. 7 Peened sample by PEMHP ($f = 500$ Hz, $v_s = 25$ mm/s)

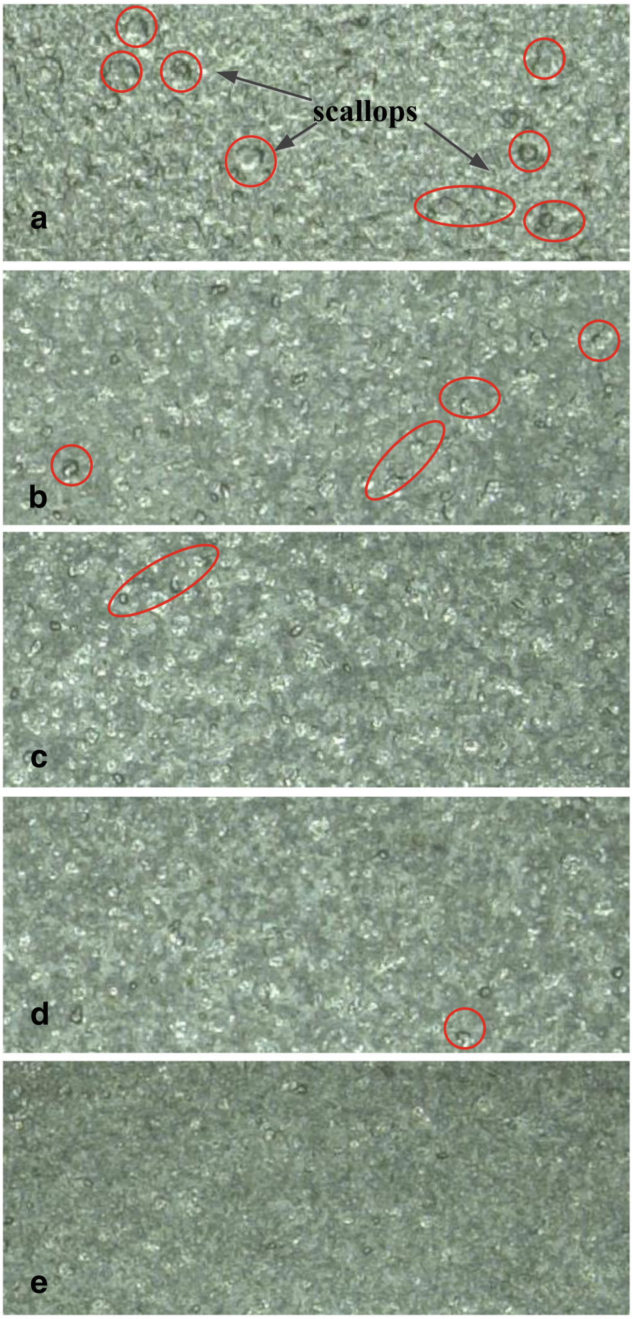

Fig. 8 Surface topography of PEMHP samples (× 50 magnification). (a) Original surface. (b) $f = 100$ Hz. (c) $f = 200$ Hz. (d) $f = 300$ Hz. (e) $f = 500$ Hz ($s = 0.1$ mm)

hardness was 208 HV, and the hardness was improved about 14–33% with different peening parameters after PEMHP. The maximum average hardness under different peening parameters is at the upper surface. The upper surface hardness values increase with increasing the peening frequency and decreasing the line pitch, but the frequency has greater influence on hardness. Meanwhile, the hardness begins to decrease sharply as the depth increases and finally turns to the original hardness at about 200 μm. Therefore, the increasing peening frequency

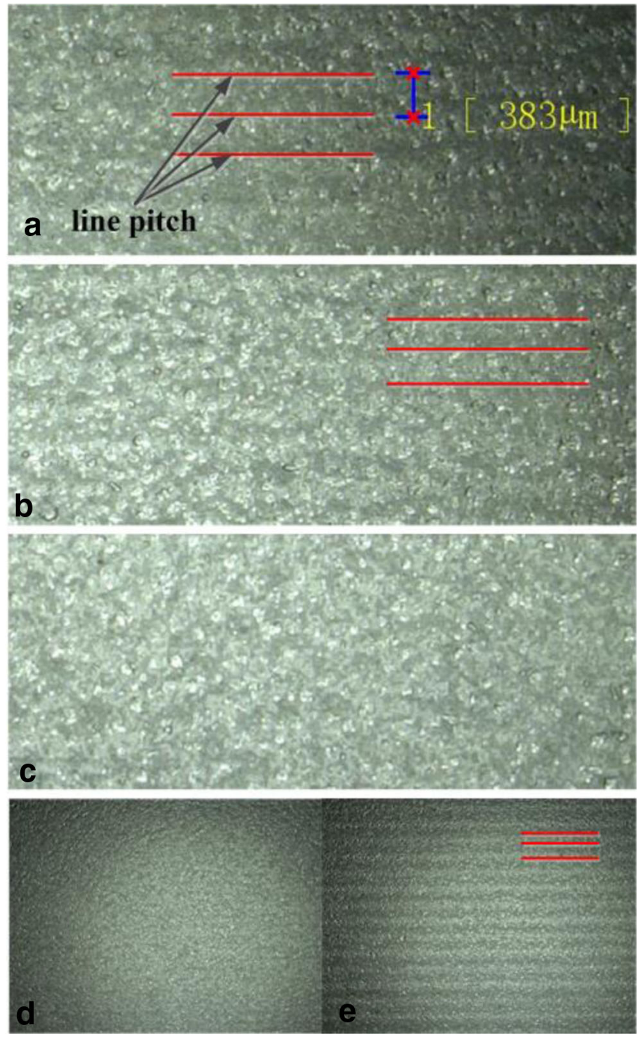

Fig. 9 Surface topography of PEMHP samples ($f = 500$ Hz). (a) $s = 0.4$ mm. (b) $s = 0.2$ mm. (c) $s = 0.1$ mm (× 50 magnification). (d) $s = 0.1$ mm. (e) $s = 0.4$ mm (× 20 magnification)

and decreasing line pitch can significantly improve the value of hardness and the depth of the hardened layer. Compared with conventional SP and UNSM, PEMHP has much the same harden improvement but less harden depth. The surface hardness and strengthened layer induced by SP and UNSM with effective external field processing, like electropulsing and laser, are more remarkable [17, 18].

3.4 Selections of peening parameters

As indicated above, the tungsten carbide tool diameter, line pitch, feed rate, and peening frequency are influencing the resulting surface roughness. In peening direction, the tungsten carbide tool diameter, feed rate, and peening frequency are the main parameters that influence the formation of surface texture. The effective machining selections of peening parameters are discussed. Unlike milling process, PEMHP may fail to hammer peening surface when using inappropriate peening

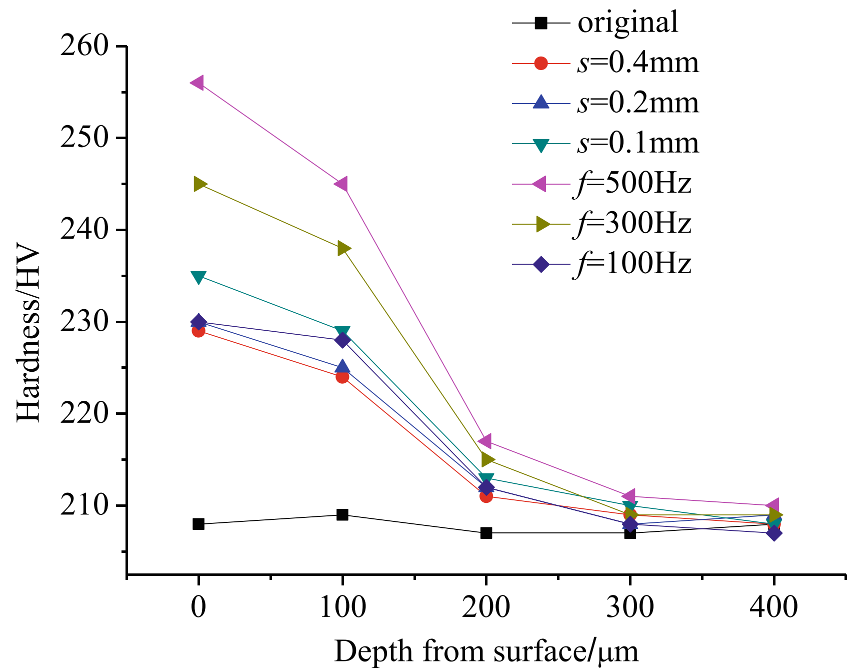

Fig. 10 Anodized aluminum alloy hardness after PEMHP

parameters. The distance of two hits should be less than a certain value as shown below.

$$s^{'} < 2\sqrt{D{\cdot}a_{\mathrm{p}}-a_{\mathrm{p}}^{2}} \quad (4)$$

When the peening parameters cannot satisfy Eq. (4), some areas of the surface would not be hammer peened. As shown in Fig. 11, the peening parameters located in the effective peening zone make PEMHP available.

Small feed rate and line pitch, large tungsten carbide tool diameter, and peening frequency can decrease the surface roughness values. On the other hand, small pitch and large peening frequency improve the hardness. The line pitch and tungsten carbide tool diameter are the main peening parameters in the vertical peening direction. It was observed that the surface roughness values decrease go along with increasing tungsten carbide tool diameter and decreasing line pitch. Therefore, it can be summarized that the choice of a large

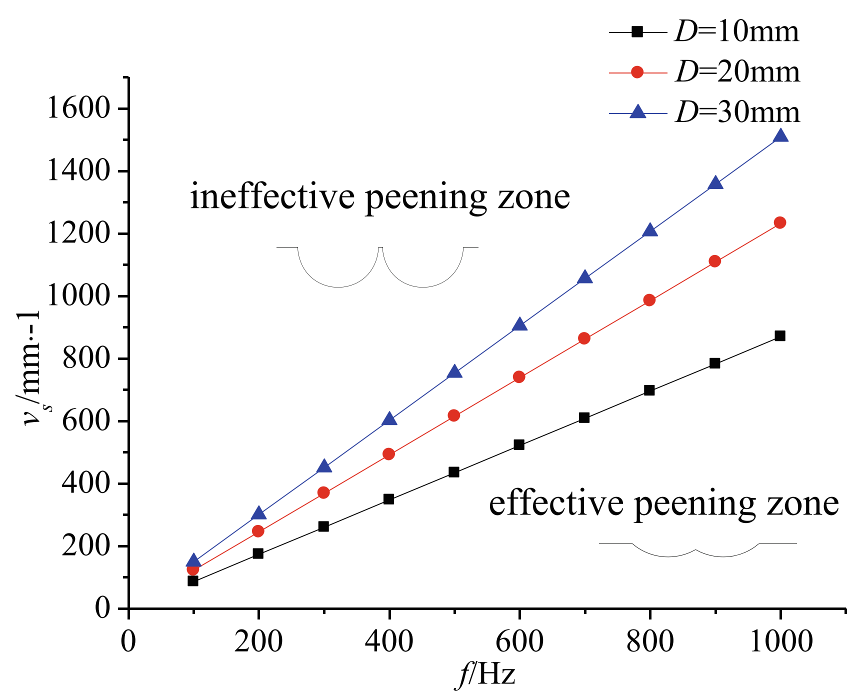

Fig. 11 The ranges of effective peening parameters

tungsten carbide tool diameter and peening frequency in combination with a small line pitch and a small feed rate can reduce surface roughness and improve the hardness. However, small feed rate and line pitch turn to low efficiency, which should be considered in the production.

4 Conclusions and future work

Based on the measured surface roughness and surface topography, PEMHP has the same surface smoothing effect as the other MHP and improves the surface integrity and hardness of 6016 anodized aluminum alloy. The peening parameters, especially line pitch, have strong influence on the surface roughness. Small line pitch and large peening frequency are good for surface peening. The simulation and experimental results showed that PEMHP had a better finishing effect and improved the hardness. Hence, it is a suitable surface treatment to improve the surface integrity and hardness of anodic oxidation further. Even more, PEMHP can be used to partly substitute the time-consuming and cost-intensive surface polishing process with appropriate peening parameters.

However, the present study found that lateral force could damage the piezoelectric actuator. The future works will focus on large stroke PEMHP and turn to hammer peening freeform surfaces with a robot. Another investigation will be carried out to improve the surface tribological characteristics by using PEMHP.

Acknowledgments The authors wish to thank Xiamen University and Winjoin Technology Co. Ltd. for providing experiment devices. We especially like to thank ZZ Wang for consulting.

Funding information We also like to thank Fujian's Education Research Project (No. JAT170429), Natural Science Fund (No. 2018J05095), and Xiamen University of Technology Climbing Project (XPDKQ18002) for financial support.

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